# Tall Buildings: Outrigger-Belt truss system vs. Framed Tube system

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## 1. ABSTRACT

In this paper, the design of two identical new office tall buildings (49 stories and 200 meters height) is carried out in order to illustrate the structural behavior of two lateral load resisting systems. Lateral loads, which tall buildings suffer from due to their high slenderness and flexibility, are of major importance in modern design methods. The paper consists of two parts. In the first part, a preliminary design has been carried out for two structural arrangements with different lateral load resisting systems and a comparison made in order to select the most appropriate for the particular tall building. The systems designed are: outrigger-belt truss system and framed tube system. These have an applicable height range up to 60 stories. The height range of these structural arrangements is generally appropriate for buildings without serious plan or vertical irregularities. In the second part, the scheme selected is designed in detail either by hand calculations or using computer software.

## 2. INTRODUCTION

Lateral load resisting systems are grouped into specific categories, each with an applicable height range. Four classical systems of this kind are: the core braced system (up to 20 stories), the rigid frame (up to 20 stories), outrigger-belt truss system-OBT (up to 50-60 stories) and framed tube-FT (up to 60 stories). The OBT and FT systems have been studied in this paper.

## 3. DESCRIPTION OF THE LAYOUT OF THE STRUCTURAL SYSTEMS

The layout of the buildings in plan is shown in Figures 1 and 2. In Figure 3, the form and the position of the vertical trusses and outriggers for OBT system, as well as the front elevation of FT system, are shown. It is obvious that the lateral system of the core in y direction is moved towards the ends of the outrigger system. In order to avoid extreme torsion of the building due to the action of lateral loads, the stiffness in both directions must be similar. Therefore, care should be given in the design of the diagonals of the vertical and horizontal trusses which would be different in each direction. The columns will be circular as this shape ensures high torsional stiffness.

As shown in the figure below, the ground plan is an octagonal. The total floor area of the building is 1887,5 $m^2$ with the largest dimension being 50 m. The height of the ground floor is 8 m while a typical floor has 4 m. The core is a rectangle of 15 m side. The area of the core is 225 $m^2$ which is approximately 15% of the total. Thus, the net floor area is 85% of the gross area. The occupancy level of office buildings is one person per 10 $m^2$ of the net floor area. Therefore, the occupancy is 167 persons. Enough lifts should exist in order to accommodate roughly half of the occupants on a typical floor (84 people). In order to fulfill this requirement, four 16-person lifts and three 10-person lifts are installed as shown in the plan view. In addition to these lifts, one firefighter lift has also been settled. The staircases are two with a width of 2 m. These will be used mainly in case of fire and they should have a position in order to ensure clear root to the exits. The toilet area provided is roughly 35 $m^2$. Finally, a storage area of 9 $m^2$ and a service core of 13,8 $m^2$ (4,2x3,3 m) are also provided.

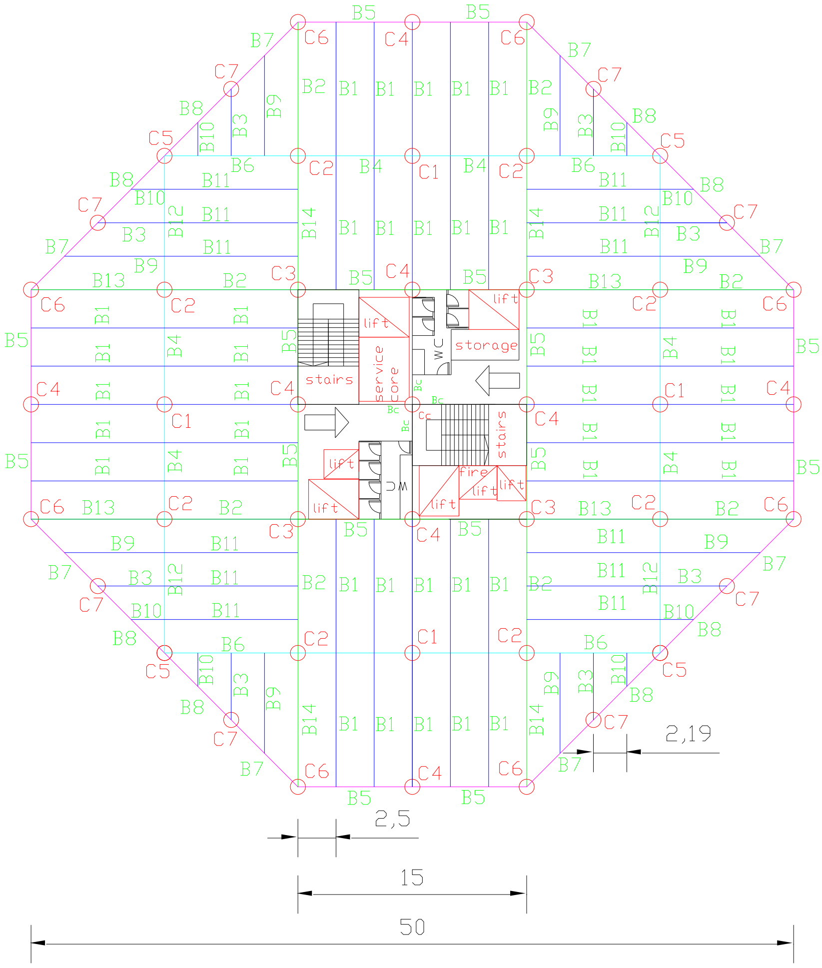


*Fig. 1: General layout of the building in plan- Outrigger system.*

As shown in Figure 3, there are three outriggers positioned at 64-72 m, 128-140 m and 192-200 m having a height of 8 m at each level. In x direction, the core consists of two vertical trusses, one at each side of perimeter of the core area, which have the form of “fishbone”. The diagonals span between three floors having a length of 10,9 m. In y direction, the lateral loading is mainly resisted by four vertical trusses connected through

the outriggers to the peripheral columns. These vertical trusses have a different form that is a warren truss. The length of the diagonals is 11,8 m.
The belt trusses are shown in pink color in Figure 1 and it is obvious that they are positioned only along the perimeter of the building. Their height is the same with the outriggers and their form is also the same. Their aim of use is to connect all the peripheral columns together and make them part of the lateral load resisting system.

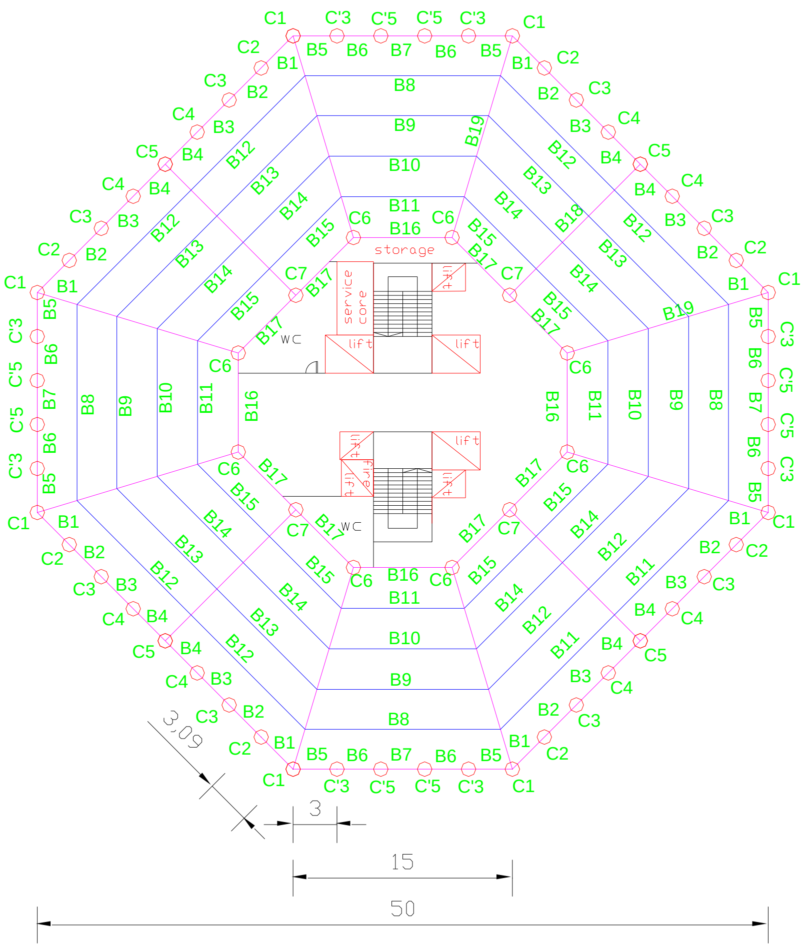


*Fig. 2: General layout of the building in plan- Framed tube system.*

The layout of the building for the FT system is shown in figure 2. It is obvious that the system consists of closely spaced columns and deep beams, which called spandrel beams, in order to connect the columns and make the lateral load resisting system. The distance between the external columns from centre to centre is 3 or 3,09 m depending on the side of the building. Secondary beams are depicted in blue while primary in pink. The distance between the secondary beams varies between 2,5 to 2,78 m due to the different lengths which are smaller near the core. The total area of a typical floor is the same as in the previous scheme. The area of the core is 382,22 $m^2$ which is 20% of the gross floor area. The net area is then equal to 1505,28 $m^2$ and the occupancy is 151 people. In order to allow enough lifts in the floor plan to accommodate roughly 76 people three 16 person lifts and three 10 person lifts are installed. Firefighter lift is also provided. Storage area and toilets are provided in plenty of space, too.

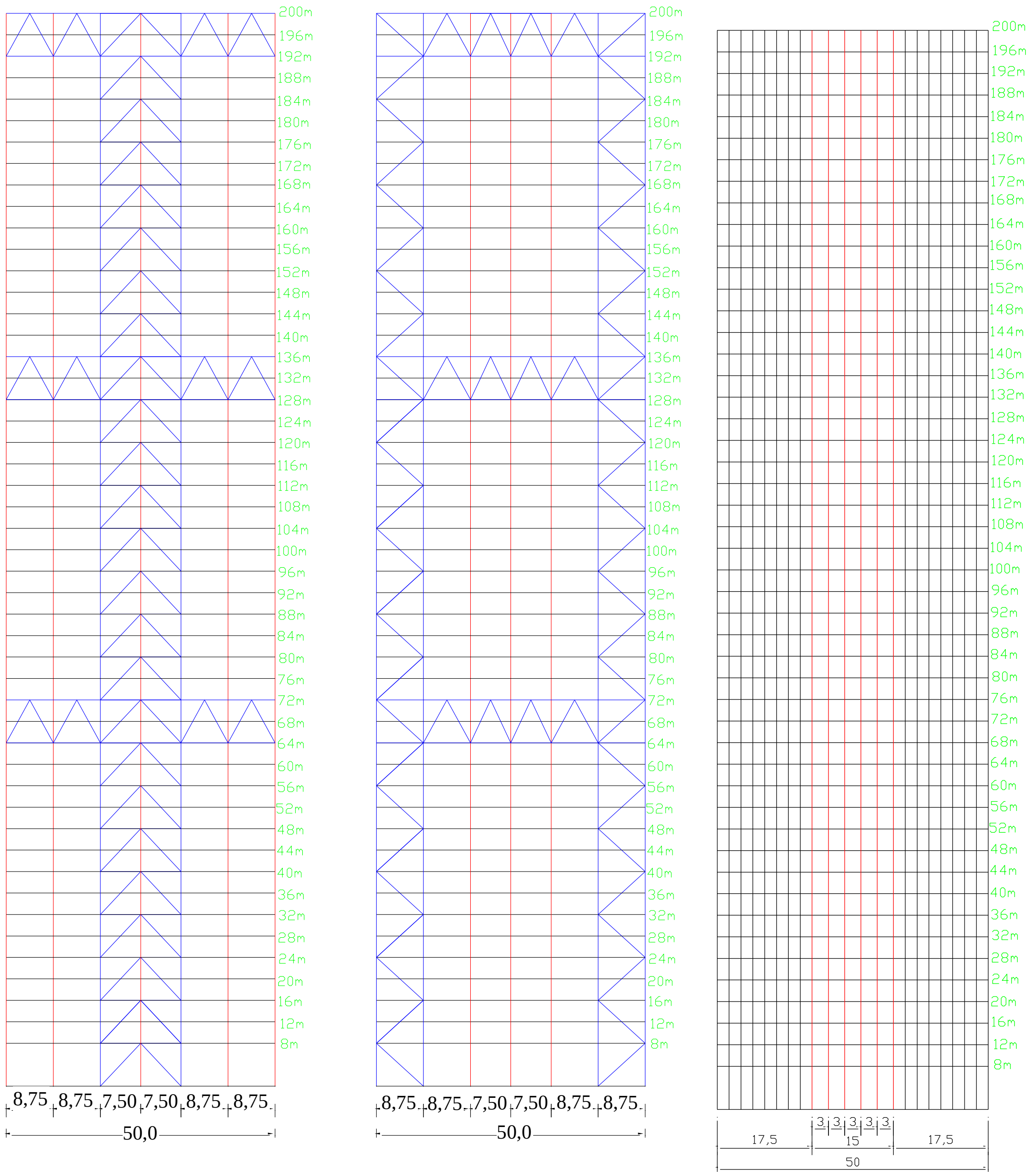


*Fig. 3: Elevations in x, y directions for OBT system and front elevation for FT system.*

## 4. PRELIMINARY DESIGN

The calculation of the wind loads of the tall building, which are similar for both schemes, made according to BS 6399- Part 2 taking into account the simplifications and assumptions mentioned in the Appendix A of the brief. The wind loads are calculated according to cl. 2.1.3. of BS. The values are different for each part of the wall face considered according to the method used with a highest value of 319,7 KN per story imposed on the last 9 stories of the building. The values of the wind loads per story are multiplied by the factor 1,4 (table 2 of BS 5950-Part 1) in order to be more conservative for the preliminary design and compensate for having considered a more favorable wind load case.

For the preliminary design the following values of dead loads are assumed:

Floor system: slab of 0,15 m depth gives a load of 3,75 $KN/m^2$, additional load due to ceiling 0,5 $KN/m^2$, steel members 0,3 $KN/m^2$ and cladding 0,5 $KN/m^2$. Then, the total load is roughly 5 $KN/m^2$. The roof is considered to carry a dead load of 5,5 $KN/m^2$ due to heavier topping that might be used. These dead loads will be used in order to design the external beams. For the internal beams there is no load from cladding and the loads are equal to 4,5 $KN/m^2$ for the typical floors and 5 $KN/m^2$ for the roof. The imposed loads that will be used are: 5 $KN/m^2$ for the offices, 3 $KN/m^2$ for the domestic floors and 4 $KN/m^2$ for the roof. The most critical load case according to BS 5950-Part 1 for the gravity loads is 1,4xDead Load + 1,6xImposed Load.

The groups of beams and columns are illustrated in figures 1 and 2. The connections are assumed to be pinned both for primary and secondary beams, which are designed as Universal Beams. The difference is that spandrel beams (deep beams) used for the outer tube of FT system are assumed to have fixed end conditions The columns will be design as concrete-filled circular hollow sections following the procedure described in EC4 (EN 1994-1-1).

In order to suggest the most appropriate structural system for the particular tall building, comparisons between the two systems have been made in terms of cost, deformations and simplicity of construction.

In order to estimate the cost indirectly, the masses of concrete and steel of all the structural elements are defined for both of the schemes. The slabs are considered of similar depth for both systems and are not included in the masses. Thus, for the outrigger system the total amount of steel used is 7828,4 tones while the total amount of concrete used is 6354,5 tones. In addition to this, for the framed tube system the total amount of steel used is 9870,5 tones while the total amount of concrete used is 9945,9 tones.

The outrigger system needs almost 21% less steel and 36% less concrete. However, these values have to be compared in relationship with the drifts obtained. The total flexural drift for the outrigger system is 45 mm while the total shear drift is 259,5 mm. The total deformation of the building is then 304,5 mm. The total flexural drift for the tubed system is 102,38 mm while the total shear drift is 169,03 mm. The total deformation of the building is then 271,41 mm.

There is a reduction of almost 11% in the total drift which is disproportional to the greater mass of the materials used.

It is also important to make a comparison for both schemes between the values of the total inter story drift and the limit for the serviceability check. In general the total inter story drifts are a bit higher for the outrigger system. In addition to this, for the framed tubed system a higher amplification factor is used. These mean that might the material used for the framed tube system could be reduced somehow.

In terms of ease of construction, the use of composite columns for both schemes makes the erection of columns easier. However, the elements are more both for beams and columns for the framed tube system and this might be more time-consuming in the construction.

For the above mentioned reasons, it seems that the outrigger system is more efficient for this particular project.

## 4. DETAILED DESIGN

The composite floor deck that will be used is the ComFlor 60 according to corus ComFlor composite decking systems. This category of composite floor is appropriate for typical unpropped span in the range of 3 to 4,4 m. Two states have been considered in the design

of the composite slab. The first one is the temporary construction phase and the second one is the permanent service state.
The beams, either secondary or primary, will be designed as composite according to EC4 specifications and basically using simple construction principles. In the design of the secondary beams only permanent state is considered. The effective widths of flanges of the composite beams are defined according to cl. 5.4.1.2 of EC4. The design shear resistance of a headed stud automatically welded in accordance with EN 14555 is determined according to cl. 6.6.3.1 of EC4. Vibration of floors has also been considered. For concrete, the dynamic modulus of elasticity is considered to be 10% higher than the static modulus. Regarding the boundary conditions of the main beams it could be assumed that for small amplitudes as they occur in vibration analysis, the beam-column connection provides sufficient rotational restrain, i.e. the main beams could be considered to be fully fixed. However, they considered conservatively simply supported. The secondary beams are ending in the primary beams which are open sections with low torsional stiffness. Thus, these beams may be assumed to be simply supported.
Columns are designed as composite circular hollow sections. Axial Forces due to wind are kept the same as in the preliminary design. There is only difference in the axial forces due to gravity loads. The axial forces are smaller than these found in the preliminary design. The moments due to the eccentricities of beams have been considered. Local buckling is considered in order to define the section. The check for creep and shrinkage is also carried out. Second order effects are considered. Finally, according to Table 2 of BS 5950-1, the check for overturning of the columns has been done for a load combination 1,0xDead Load + 1,4xWind Action.
The computer software SAP2000 is used to validate the detailed analysis. Columns are considered fixed at the ground. Pinned connections exist at the points where the columns intersect with the belt trusses and the outriggers. Pinned joints also used at the points where the members of belt trusses, outriggers and bracings intersect. Diaphragmatic action considered at each floor level. The sections that are used for the outriggers and belt trusses for each part are the same as defined in the preliminary design. Except for the basic load combinations, analysis of the model made for the Notional Horizontal Load in order to take into account the P-Δ effects and find the amplification factor $K_{amp}$ according to the displacements derived from SAP.
The maximum displacement at the top of the model in SAP is 326,3 mm. The hand calculations give values less or equal to 307,8 mm. In general, the comparison between the displacements from the SAP analysis and the detailed design shows that the deviations in the values of deformations are mostly less than 10%. Most of the displacements calculated in the detailed design are higher than these of the model in SAP, especially at the bottom part of the structure (1-10 floors) with differences reaching 14%. The analysis showed that the serviceability limit check is not fulfilled for all stories and this implies that sections of the elements and mainly of columns have to be changed. This is the case basically for the top part (34-45 floors) of the building. The other parts with the large composite columns are more rigid and in general are adequate. However, inaccuracies of the model have to be considered due to the fact that the composite columns are defined indirectly through material properties and might this makes in general the model less stiff than considered in the detailed design. In addition to this, it is important to mention that the formulae of displacements used in the detailed design are based on the assumption that the outriggers are infinitely rigid. In the model, this is not considered directly (very large sections are used). Moreover, there is much difference in the displacements due to second order effects. In general, the analysis in SAP gives much lower values of inter-story drifts and $\lambda_{cr}$ is generally more than 10. The Kamp equals to 1,015 while in the detailed design Kamp is

1,045. Thus, the stability of the structure seems not to be an important matter for the model. In the detailed design is a more significant issue. However, the serviceability limit might be conservative enough. Finally, it should be mentioned that the sections of the columns inserted in the model are designed in detail taking into account second order effects. Thus, it is possibly logical that the need for the loads to be amplified again is less.

## 5. CONCLUSIONS

The FT system seems to be more efficient in reducing the shear drift which can be more critical in cases of other later loads such as earthquake. However, most of the OBT systems use a concrete core which overcomes the problem of larger shear drifts. When a steel core is used, this needs to be quite deep. The outrigger system is certainly the most popular nowadays for a lot of tall buildings in both seismic and non-seismic zones. In Figure 4 the total deformations of each story and the deformations for P-D effects are presented for both detailed and SAP analysis.

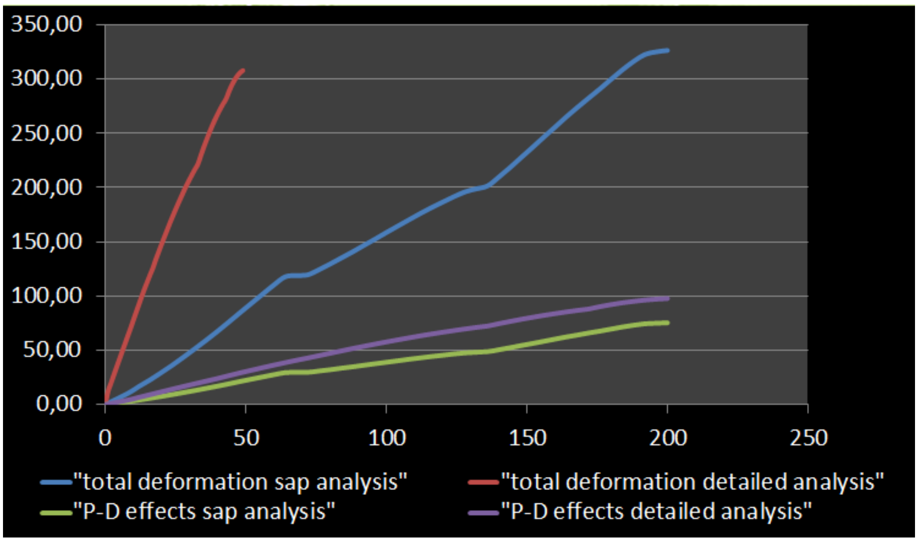


*Fig. 4: Total deformations and P-D effects.*

## 6. ACKNOWLEDGEMENTS

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**ΠΕΡΙΛΗΨΗ**

Σκοπός αυτής της εργασίας είναι ο σχεδιασμός δύο πανομοιότυπων κτιρίων γραφείων 49 ορόφων (συνολικό ύψος 200 μέτρα) με στόχο τη μελέτη της συμεριφοράς δύο διαφορετικών συστημάτων ανάληψης πλευρικών φορτίων. Τα πλευρικά φορτία καταπονούν κυρίως τα ψηλά μεταλλικά κτίρια, τα οποία παρουσιάζουν μεγάλη λυγηρότητα και ευκαμψία. Αρχικά διεξάγεται μία προμελέτη των δύο κτιρίων και γίνεται μια πρώτη σύγκριση της συμπεριφοράς των δύο συστημάτων. Με βάση τα συμπεράσματα όσον αφορά το κόστος υλικού, τις απαιτήσεις λειτουργικότητας και την ευκολία κατασκευής επιλέγεται η καταλληλότερη διάταξη. Τα δύο συστήματα που μελετώνται είναι: 1) το σύστημα με διατμητικά πλαίσια στον πυρήνα καθώς και περιφερειακά και εγκάρσια δικτυώματα και 2) το σύστημα πυκνής πλαισιακής δομής στην περίμετρο του κτιρίου (συμπεριφορά του κτιρίου σαν πρόβολος με σωληνωτή διατομή). Το συστημα που επιλέγεται είναι το πρώτο και αυτό σχεδιάζεται λεπτομερώς.